Linear Actuators
for Locomotion of Microrobots

by

Haiwei Lu

M.Eng., B.Eng. (Elec.)

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CERTIFICATE OF AUTHORSHIP / ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Name of Candidate: **Haiwei Lu**

Signature of Candidate:

Lu Haiwei 03 / 10 / 2007

To my mother, my wife, and my daughter

ABSTRACT

The successful development of the miniaturisation techniques for electronic components and devices has paved the way for the miniaturisation in other technological fields. In the past two decades, the research achievements in micromechatronics have spurred fast development of micro machines and micro robotic systems. Miniature or micro actuators are the critical components to make these machines more dexterous, compact and cost effective.

The main purpose of this dissertation is to develop micro actuators suitable for the locomotion of an in-pipe or endoscopic microrobot. The content of the thesis covers the selection of the actuation principle, robotic system design, actuator design and prototype construction, performance analysis, and design, analysis, and implementation of the appropriate drive control system.

Among different types of actuation principles, piezoelectric and electromagnetic actuators are the two major candidates for the micro robotic systems. In order to find a suitable actuation principle for the desired robotic application, a comparative study was conducted on the scaling effects, attainable energy density, and dynamic performances of both types of actuators. Through the study, it was concluded that the electromagnetic actuator is more suitable for the endoscopic microrobot.

Linear actuators are the common design used for the locomotion of microrobots due to many advantages compared to their rotational counterparts. Through a thorough review and comparison of the electromagnetic linear actuator topologies, a moving-coil tubular linear actuator was chosen as the first design due to its simplest structure. Via the magnetic circuit analysis and numerical magnetic field solutions, the actuator was designed for optimum force capability, and the electromagnetic force and the machine parameters of the actuator were predicted. According to the results obtained from the magnetic field analysis, the dynamic model of the actuation system with a driving control scheme was established and used in the actuation performance analysis of the robotic system.

Based on the experience achieved through the first design, a new moving-magnet tubular linear actuator was designed. The methodology developed in the design and analysis of the moving-coil linear actuator was adopted for the moving-magnet actuator design. However, the optimal design is more complicated due to the multi-pole and multi-phase structure of the moving-magnet actuator. The electromagnetic force of the actuator was analysed under the condition of different excitation methods. An enhanced parameter computation method is proposed for predicting the actuator parameters. Based on the results of magnetic field analysis, a comprehensive dynamic model of the actuator was developed. Through the coupled field-circuit analysis, this model can predict accurately the dynamic performance of the actuator. The characteristics analysis shows that the performance of the moving-magnet actuator is much better than that of the moving-coil actuator.

Two prototypes of the moving-magnet tubular linear actuator with different dimensions were constructed to verify the performance and the scaling theory. Various precision machining techniques were employed during the fabrication. The performances and parameters of the two different prototypes were measured and the results agree substantially with the theory.

The brushless DC drive method was chosen for the driving control of the proposed linear actuator because of the compact circuit topology and simple implementation, which are two essential factors for micro applications. A sensorless control scheme based on the back EMF was developed as physical position sensors are not permitted in such a micro system. The control scheme was then applied to the locomotion control of the proposed microrobot. The system simulation shows that the control performances of both the actuator and microrobot are satisfactory.

A dSPACE prototyping system based driving control hardware was designed and implemented to experimentally verify the control design. The experimental results agree substantially with the theoretical work.

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LIST OF SYMBOLS[1]

$\vec{A}$	Magnetic vector potential (Wb/m)
A	Area (m^2)
A_c	Cross sectional area of a conductor (m^2)
A_{cl}	Area enclosed by a coil (m^2)
A_g	Cross sectional area of an air gap (m^2)
A_p	Contact area (m^2)
A_s	Surface area of a conductor (m^2)
$\vec{B}$	Magnetic flux density vector
B_g	Flux density in an air gap (T)
B_{gr}	Radial component of flux density in an air gap (T)
B_m	Magnetising flux density in a phase winding (T)
B_r	Radial component of flux density (T)
C_d	Clamped capacitance (SI)
D_i	First-rank tensor electrical displacement (C/m^2)
d_{ikl}, d_{in}, d_{mk}	Third-rank and second-rank tensor piezoelectric constant (m/V)
E	Electrical field strength (V/m)
E_k	First-rank tensor electric field strength (V/m)
E_m, e_m	Back electromotive force caused by permanent magnets (V)
$\hat{E}_m$	Complex notation of E_m
e_s	Back electromotive force caused by machine saliencies (V)
F	Force (N)
$\hat{F}$	Complex notation of force
F_{em}	Electromagnetic force (N)
F_{emm}	Electromagnetic force generated by permanent magnets (N)
F_{emp}	Electromagnetic force under one pole (N)
F_{ems}	Electromagnetic force generated by machine saliencies (N)

[1] Symbols which are not listed here are defined where they appear.

F_f	Frictional force (N)
F_{load}	Load force (N)
F_{mm}	Magnetomotive fore (A·t)
F_N	Normal force (N)
F_{sp}	Elastic force of a spring (N)
g	Length of an air gap (m)
$\vec{H}$	Magnetic field strength vector
H_c	Coercive force of a permanent magnet (A/m)
h_c	Height of a coil (m)
h_d	Thickness of friction layer in an ultrasonic motor (m)
h_m	Height of a permanent magnet (m)
h_p	Penetration of stator into friction layer in an ultrasonic motor (m)
h_s	Thickness of a piezoelectric segment (m)
I, i	Current (A)
$\hat{I}$	Complex notation of current $\hat{I} = Ie^{j\omega t}$
I_0	*rms* value of phase current (A)
I_1	Conductor current (A)
I_m	Field excitation current (A)
I_{rated}	Rated winding current (A)
$\vec{J}$	Current density vector
J	Current density (A/m^2)
J_s	Effective current density (A/m^2)
K_e	Back electromotive force coefficient (V·s/m)
K_f	Force coefficient (N/A)
K_{sp}	Elastic constant (N/m)
k_d	Deformation coefficient of friction layer in an ultrasonic motor
k_{ff}	Fill factor
k_m	Magnetic occupation ratio
k_p	Coefficient of restitution
k_T	Thermal conductivity (W/m·K)
k_v	Wave number of a plane wave
L	Inductance (H)

L_a	Self inductance of a coil (H)
L_1	Self inductance of a conductor (H)
L_{1m}	Mutual inductance between a conductor and an excitation coil (H)
L_m	Self inductance of an excitation coil (H)
L_{jk}^{app}	Apparent inductance between windings j and k (H)
L_{jk}^{diff}	Differential inductance between windings j and k (H)
$\vec{l}$	Length vector
l_c	Length of a conductor, or mean circumference of a coil (m)
$\vec{M}$	Magnetisation vector (A/m)
m_a	Mass of a moving coil or translator (kg)
m_s	Mass of a stator (kg)
N_t	Number of turns of a coil (turns)
p	Pressure (N/m^2)
Q	Heat flow (W)
R	Resistance (Ω)
R_a	Winding Resistance (Ω)
R_{coil}	Coil resistance (Ω)
R_{ph}	Phase resistance (Ω)
r_c	Radius of a conductor or mean radius of a coil (m)
r_r	Effective radius of rotor ring in an ultrasonic motor (m)
S_{ij}, S_m	Second-rank and first-rank tensor mechanical strain
s_{ijkl}, s_{mn}	Fourth-rank and second-rank tensor elastic compliance coefficient (m^2/N)
s_{ijkl}^E, s_{mn}^E	Elastic compliance coefficient at constant electric field (m^2/N)
T	Temperature (K)
T_{kl}, T_n	Second-rank and first-rank tensor mechanical stress (N/m^2)
U, u	Voltage (V)
$\hat{U}$	Complex notation of voltage $\hat{U} = Ue^{j\omega t}$
U_0	*rms* value of phase voltage (V)
u_{a0}, u_{b0}, u_{c0}	Phase terminal voltages (V)
u_n	Neutral voltage (V)
V	Volume (m^3)

v_a, v_m	Velocity of a moving coil and a translator, respectively (m/s)
v_r	Rotor velocity (m/s)
v_s	Stator velocity (m/s)
W_E	Electrical field energy (J)
$[W_E]$	Electrical field energy density (J/m^3)
W_M, W'_M	Magnetic field energy and co-energy (J)
$[W_M]$, $[W'_M]$	Magnetic field energy density and co-energy density (J/m^3)
x, y, z	Cartesian coordinates
$\hat{x}$	Complex notation of x
$\dot{x}$	dx/dt
$\hat{\dot{x}}$	Complex notation of $\dot{x}$
Y	Young's Modulus
Z, Z_0	Elastic impedances of a piezoelectric actuator
ε	Electrical permittivity (F/m)
ε_r	Relative electrical permittivity
ε_0	Electrical permittivity of free air (F/m)
$\varepsilon_{ik}^T, \varepsilon_{ik}^S$	Electrical permittivity at constant stress and strain, respectively (F/m)
θ	Angle between a stationary and a moving windings
λ_j	Flux linkage of the j-th winding (Wb)
λ_m	Magnetising flux linkage (Wb)
λ_{jk}	k-th component of λ_j (Wb)
μ	Magnetic permeability (T·m/A)
μ_0	Magnetic permeability of free space (T·m/A)
μ_f	Coefficient of friction
μ_m	Permeability of a permanent magnet (T·m/A)
μ_r	Relative magnetic permeability
v_{ph}	Phase velocity of a plane wave
ξ	Characteristic size of an object
ρ	Resistivity (Ω·m)
ρ_e	Resistance per meter (Ω/m)
ρ_m	Mass density of a piezoelectric material (kg/m^3)
Γ	Torque (N·m)

τ	Pole pitch (m)
τ_c	Thickness of a pole-piece (m)
τ_m	Thickness of a permanent magnet (m)
Φ	Electromechanical coupling factor
ϕ	Magnetic flux (Wb)
ϕ_g	Magnetic flux in an air gap (Wb)
ϕ_p	Magnetic flux per pole (Wb)
ω	Angular frequency or speed (rad/s)
$\mathscr{F}$	Magnetic scalar potential (SI)
$\Re$	Reluctance (SI)
$\Re_g$	Reluctance of an air gap (SI)
$\Re_m$	Reluctance of a permanent magnet (SI)

LIST OF ACRONYMS

2D	Two-Dimensional
3D	Three-Dimensional
AC	Alternating Current
CAD	Computer Aided Design
DC	Direct Current
DOF	Degree of Freedom
DSP	Digital Signal Processors
ECDM	Electro-Chemical Discharge Machining
EDM	Electrical Discharge Machining
EMF	Electromotive Force
FE	Finite Element
FEM	Finite Element Method
FMA	Flexible Micro Actuator
GMM	Giant Magnetostrictive Material
GUI	Graphical User Interface
IDM	Impact Drive Mechanism
LIGA	*German:* Lithographisch Galvanoformingung und Abformung
LIM	Linear Induction Machines
LRM	Linear Reluctance Machine
LSM	Linear Synchronous Machine
MIS	Minimally Invasive Surgery
MMF	Magnetomotive Force
NdFeB	Neodymium Iron Boron
PM	Permanent Magnet
PWM	Pulse Width Modulation
PZT	Lead Zirconate Titanate
RTI	Real-Time Interface
SMA	Shape Memory Alloy
SME	Shape Memory Effect

SmCo	Samarium-Cobalt
SPWM	Sinusoidal PWM
TLA	Tubular Linear Actuator
ULSI	Ultra Large Scale Integration
ZCP	Zero-Crossing Point

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